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Suspended Submicron Silicon-Beam for High Sensitivity Piezoresistive Sensing

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Abstract

This paper presents a submicron suspended piezoresistive silicon-beam structure as a basic sensing element to replace the conventional piezoresistors, so to improve the detection sensitivity. The alternative element benefits from the increase of the induced stress, which is locally concentrated on the suspended submicron beam. This approach allows the enhancement of sensitivity without modifying the parameters in the mechanical design. A modified deep reactive-ion etching process is developed to create both the suspended silicon-beam and the main mechanical structure in a single etching sequence. With the new element, sensitivity up to 52.5 V/N is obtained, corresponding to a 120% improvement compared to an equivalent structure with conventional piezoresistors.

Keywords: piezoresisitve sensor, force detection; deep reactive-ion etching; submicron suspended silicon-beam;

1. Introduction

Piezoresistive sensors have been widely used in force detection, pressure sensors and accelerometers [1], due to their small scale, easy integration and convenient readout method. To improve sensitivity for a higher signal-to-noise ratio and thus minimum detectable force, modification of geometry and size of the mechanical elements, i.e. longer but narrower beams, or larger but thinner membranes are often required. However, such modifications cause big variation in stiffness and resonation frequency of the mechanical structure, and sometime encounter fabrication limitations. As a result, the mechanical structure together with the fabrication method needs to be reconsidered. To avoid this, an alternative way to improve the sensitivity of the device is to use more sensitive elements, such as sub-micron silicon wires [2], to replace the conventional piezoresistive sensors, while keeping the mechanical structure and fabrication process

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essentially unaltered. In this paper, a suspended submicron silicon-beam is proposed as an alternative piezoresistive sensing element to address the abovementioned challenges.

2. Design & Analysis

A basic force sensing cantilever is used to demonstrate the proposed concept. Fig.1 schematically shows a force sensing cantilever integrated with a conventional piezoresistor (Fig.1a) and the proposed suspended submicron silicon-beam (Fig.1b). The silicon-beam is locally suspended on the top surface of the silicon cantilever. The cavity under the beam gives a non-symmetric geometry along the direction of the thickness, and therefore generates an enhancement of local concentration of the mechanical stress at the beam (Fig.1c), when a fixed load is vertically applied at the tip of the cantilever. This eventually results in an improvement of sensitivity for force detection. As the new element occupies only a small part of the entire structure, the influence on the mechanical properties of the whole system is not significant.

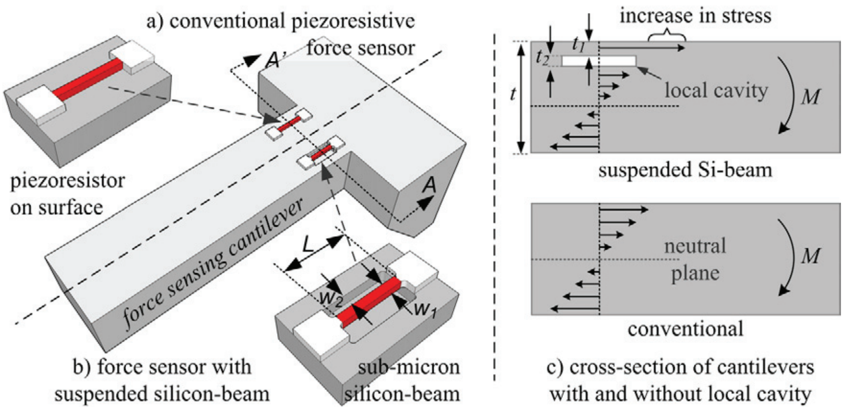

Fig. 1: Schematic drawing of a force sensing cantilever with a conventional piezoresistor (a) and a suspended silicon-beam sensor (b), as well as the stress distribution on their vertical cross-sections (c).

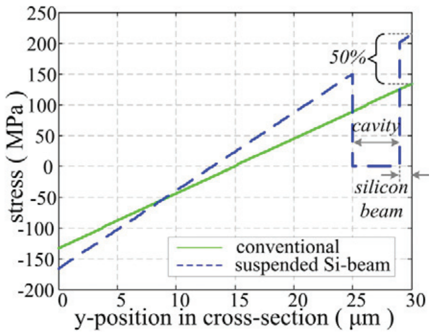

Fig 2: 1D numerical calculation of the stress distribution in cantilevers with and without a locally suspended silicon-beam.

The enhancement of the stress on the suspended beam can be roughly predicted with a 1D model. The non-uniform distribution of stress, due to the non-symmetric geometry on the vertical cross-section (Fig.1c), is calculated as shown in Fig.2. The non-uniform distribution of stress is a function of beam thickness (t_1), height of the cavity (t_2) and the thickness of the cantilever (t). For a 30 μm thick cantilever, with t_1=1μm and t_2=4μm, the distribution of the stress is shown in Fig.2 (dash line). Compared to a conventional cantilever (solid line), the increase of stress at the top surface of the cantilever is 50%.

3. Fabrication

An IC-compatible process was used to fabricate the device. The piezoresistors were defined in a 500 nm boron-doped (1.1×10^{18} atoms/cm^3) epitaxial layer (Fig.3a). All resistors were oriented along the [110] direction in (001) plane. After the metallization process, tetramethylammonium hydroxide (TMAH) was used to etch cavities from backside, thus defining the thickness of the silicon cantilevers (Fig.3b).

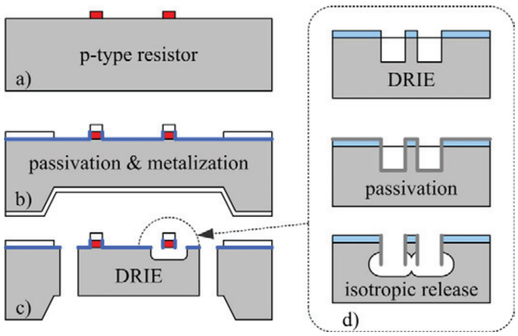

Fig. 3: Main steps of the fabrication process. The suspended beam is formed using a combination of DRIE and isotropic silicon etching process.

The lateral dimension of the submicron silicon-beam was defined by stepper lithography. In order to keep the fabrication simple, a two-step deep reactive-ion etching (DRIE) process was developed to fabricate the sub-micron suspended silicon-beam and the cantilever in a continuous sequence. In the first step, a combination of short DRIE etching and silicon isotropic etching was used to create the suspended silicon-beam (Fig.3d), where the thickness of the beam was controlled by the timing of the DRIE sequence. In the second step, standard DRIE process was performed to define the geometry of the cantilever (Fig.3c).

4. Measurement Results

Fig.4 shows SEM images of a fabricated force sensing cantilever. The cantilever is 1200 µm long, 50 µm wide and 35 µm thick.

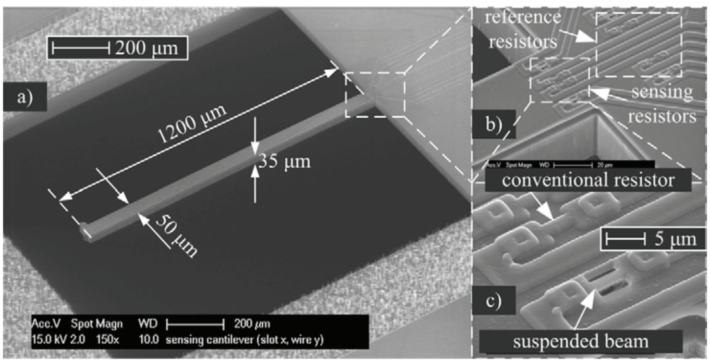

Fig. 4: SEM photos of (a) a fabricated force sensing cantilever, (b&c) close-up showing the integrated suspended sub-micron silicon-beam sensors and conventional piezoresistors.

The silicon-beam in this device was 5 µm long, 500 nm wide and around 500 nm thick. The cavity under the beam was around 3 µm deep. The conventional piezoresistor had the same dimension as the suspended beam but without the cavity. The stiffness of the cantilever with suspended silicon-beam, extracted by bending the cantilever with controlled force and displacement, was 48.1 N/m. This value is almost identical to the one of a conventional cantilever with the same geometry but without the silicon-beam. This proves that the introduced mechanical modification to the entire structure is rather small.

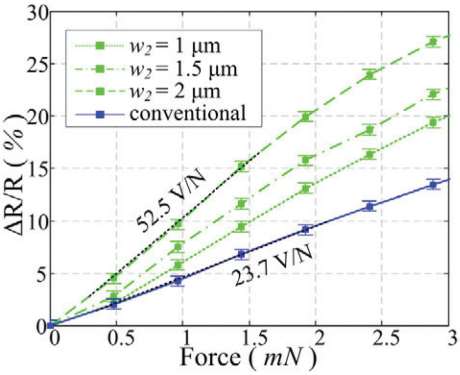

Fig 5: The response of the suspended silicon-beam (with different size of slot w_2) and the conventional piezoresistor under same mechanical loads at the free-end of the sensing cantilever.

Fig.5 shows the resistance variation of the suspended silicon-beam as a function of applied force. The silicon-beams had an approximately linear response. The sensitivity of the silicon-beam is a function of the slot width (w_2). This is due to the non-uniform geometry on the top surface of the cantilever, which causes a stress concentration between the two slots. The maximum response was obtained in a beam with w_1=0.6µm, w_2=2µm and L=5µm. The corresponding sensitivity is 52.5V/N under a Wheatstone bridge configuration with 1V DC supply. This indicates a sensitivity improvement of 120% when compared with a conventional piezoresistor tested under the same mechanical load. The theoretical thermal noise of each silicon-beam (typical resistance = 20kΩ) is 0.02 µV/Hz$^{1/2}$, corresponding to a force resolution of 0.38 nN/Hz$^{1/2}$.

5. Conclusions

A method to improve the sensitivity of force detection without modifying the mechanical design is proposed. Suspended sub-micron silicon-beams was used to replace the conventional piezoresistor. A force sensing cantilever, where the silicon-beam and the cantilever are fabricated in a continuous DRIE sequence, was fabricated with an IC-compatible process. With the proposed concept, an 120% improvement of sensitivity of the forse sensing cantilever compared with a conventional piezoresistor was measured.

Acknowledgements

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